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TECHNICAL MEMORANDUMS

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

No. 694

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COMBUSTION OF GASEOU~~S~~ MIXTURES

By R. Duchêne

Publications Scientifiques et Techniques
du Ministere de l'Air

Washington
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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL MEMORANDUM NO. 694

COMBUSTION OF GASEOUS MIXTURES*

By R. Duchene

Description of the Second Apparatus

The first apparatus not having made it possible to solve the problem, because the explosive wave was not obtained, a new apparatus was constructed which made it possible to carry the compression ratio to 7. (Fig. 1.) It was found possible to improve certain parts and more closely approximate an actual engine. The apparatus consists of a steel cylinder with a bore of 50 mm (1.97 in.) and a piston with a stroke of 295 mm (11.61 in.), as shown in Figure 2. The glass tube was discontinued, and the explosion chamber was bored in the same steel block, at the end of the cylinder. It had a volume of about 96 cm³ (5.85 cu. in.) and was closed at the end by a spark plug. In order to make it possible to photograph the flame, a narrow slot was made the whole length of the explosion chamber and hermetically closed by glass.

The carbureted mixture was introduced, in the liquid form, directly into the chamber by utilizing the suction produced by the sudden withdrawal of the piston. In order to approximate the conditions in an engine, the mixture was introduced through a nozzle which was supplied, before the test, with the desired quantity of combustible. The negative pressure produced by the inflow of air drew in the contents of the capillary tube. (Fig. 3.) The mixture consisted partly of vapor and its homogeneity was less perfect than in the preceding cases, but the events occur in a way more nearly conforming to actual practice.

The temperature of the mixture was shown by a thermometer introduced into the chamber just before the test.

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*"Etude de la combustion des mélanges gazeux." Publications Scientifiques et Techniques du Ministère de l'Air. Service des Recherches de l'Aéronautique, pp. 51-66.
This Memorandum is supplementary to N.A.C.A. Technical Memorandums 547 and 548: Contribution to the Study of Normal Burning in Gaseous Carbureted Mixtures. Parts I and II.

Electric heating wires surrounded the cylinder, making it possible to raise the inside temperature to 180°C (356°F.). The compression was produced, as in the first apparatus, by a heavy ram, weighing 40 kg (88 lb.), which was raised from its position of equilibrium and allowed to fall freely. The ignition was accomplished by means of a spark plug, and the breaking of the primary circuit of the induction coil was always controlled by the piston rod.

In order to enable the measurement of the energy developed by the explosion, the ram was mounted on ball bearings, so that the height to which it was returned by the expansion was approximated proportional to the energy exerted. The maximum height was recorded on a plate coated with lampblack. (Fig. 4.)

The film moved at the rate of 12 m (39.37 ft.) per second, its speed being controlled by an indicator.

Duration of the Compression and of the Period of Rest of the Piston

We considered it important to determine exactly the conditions under which the combustions were produced, in order to show whether the results can be compared with those obtained in an engine. It is necessary to know the duration of the compression and expansion, as also of the pause at the end of the stroke, which does not occur in an engine.

For this purpose a long luminous slot was placed behind the piston rod, so that it was totally hidden by the latter from a photograph camera placed in front. (Fig. 5.) A hole in the piston rod transmitted a ray of light which formed a point on the film. The film was mounted on a drum. When the piston was driven in by the ram, this point moved on the film along a generatrix of the drum, when the latter was at rest. When the drum was turning, the motion of the piston was recorded on the film in the form of a curve.

Figure 6 is a record obtained in this way. Combustible, "Esso"; compression ratio $r = 7$; initial temperature $t_i = 60°$ C (140°F.). It is obvious that the compression did not take place regularly, but by jumps. We cannot explain this phenomenon. The expansion, on the contrary, was very regular. The curve bends at the instant the velocity ceased to increase. It may be estimated that the time of arrest at the bottom of the stroke was of the order of 0.01 second. During this time the combustion took place at constant volume and the flame was not affected by the motion of the piston.

We considered it of interest to compare the top of this curve for different fuels. For this purpose we invented the magnifying device shown in Figure 7. Two records obtained with this device are shown in Figure 8. The fuels were "Esso" and ordinary gasoline, $r = 7$ and $t_i = 148^\circ C$ ($298.4^\circ F.$). No spark was required, as auto-ignition was produced at this temperature with both fuels. The photographic paper moved at the rate of 2.8 m (9.2 ft.) per second.

From these records we obtained the following data by taking account of the fact that the points of the curves situated on the ordinate A A' correspond to the maximum penetration of the piston. The part of the curve above this ordinate represents an elastic displacement of the whole cylinder under the influence of the thrust of the ram. Allowing for the magnification, this deformation is about 4 mm (0.16 in.).

	"Esso"	Gasoline
Period of rest of piston at bottom of stroke (max. compression) in thousandths of a second.	0.85	0.70
Velocity of return of piston at end of 1 cm (0.4 in.) of expansion stroke (per sec.).	1 m (3.28 ft.)	1.4 m (4.59 ft.)
Remarks	Velocity continues to increase below photograph.	Velocity seems to have reached its maximum before bottom of photo.

It is evident from these records and the above table that the combustion, as judged by its effects, proceeded more rapidly with gasoline than with "Esso." The time of combustion at constant volume was a little less with the former. The curves corresponding to the expansion show that the maximum velocity of combustion was reached sooner with gasoline than with "Esso."

We have given the results of the preliminary tests to show how our device differs from a real engine. The velocity of the piston in our apparatus corresponds approximately to the mean velocity of the piston in an engine running at 300 r.p.m. This is much slower than the speed of an ordinary engine running at full power, but about the same as that of a Diesel engine. Nevertheless, when fuels are investigated in a special engine, like the Armstrong, it is made to revolve at a speed of this order of magnitude. The piston is not arrested at the bottom of its stroke in an engine, but its velocity is known to pass through zero at the dead center and to be small in this vicinity.

Consideration of the Results

The second apparatus, which we have just described, gives displacement records of the flame similar to those of the first apparatus, but they are not so uniform, due to the mixture being less homogeneous. With this apparatus it would be difficult to plot curves like those in Figure 9 showing the effect of the richness of the mixture, because the differences between two identical tests are sometimes greater than those due to a variation in the richness of the fuel. One might, of course, obtain an acceptable result by repeating the tests and taking the mean of the data obtained.

Data Taken from Several Records

In order to make this point clearer, we will give, in tabular form, the numerical results of several series of tests. Although tests were made with many hydrocarbons, we will confine ourselves to the comparison of two which differ greatly as to composition and results, namely, ordinary gasoline and "benzol 90" (benzene). Here are the characteristics of these two fuels:

	S.G.	Boiling point
Ordinary gasoline ("Motricine")	0.728	31 to 200°C
Benzol 90 ("Paris gas")	0.880	78 " 110°C
		and 90 per cent at 100°C

During the tests, the richness of the mixture was always slightly greater than that of the theoretical mixture, because our previous tests showed that the combustion speed of such a mixture is the greatest. (See Table I, page 13.)

Consideration of These Results

Column 2 of Table I shows that successive tests, under as like conditions as possible, gave the following variations for θ duration of propagation.

$$\left.\begin{array}{ll}\text{Gasoline} & 4.8 < \theta < 7.2 \\ \text{Benzol} & 4.2 < \theta < 6.0\end{array}\right\} \text{in thousandths of a second.}$$

Moreover, it seems to follow from this table:

1. That the combustion as a whole (from the instant of the spark until the instant at which the flame reaches the other end of the chamber) is more rapid for benzol than for gasoline.

2. That the lag (time between passage of spark and beginning of propagation) is smaller for benzol than for gasoline. If this difference in lag is taken into account, it seems that the actual period of propagation is practically the same for both hydrocarbons.

3. That both the lag and the difference in the duration of the propagation increase, when the time allowed for the formation of the mixture (called "delay" in the table) decreases.

We have stressed the importance of the discrepancies between two consecutive tests, in order to show that no conclusion can be drawn from a single test and that any conclusion must be drawn from the mean results of as large a number of tests as possible. It is by proceeding in this manner that we have established the few following points.

Effect of the Initial Temperature of the Cylinder

It is interesting to consider first the effect of the temperature of the mixture on the mean propagation velocity of the flame. Table II summarizes the results obtained with several fuels. The numbers indicate the time, in thousandths of a second, required for the flame to traverse the 10 cm (3.93 in.) explosion chamber. (See Table II.)

The effect of the initial temperature is considerably below 50°C (122°F), the mean velocity doubling when the temperature rises from 15 to 50 or 60°C (59 to 122 or 140° F). Above this temperature the velocity does not seem to vary much. The combustion velocity of the heavy gasolines is greatly increased by the addition of benzol. The diameter of the tubes seems to have no appreciable effect above 15 mm (0.6 in.). Under these conditions the velocities obtained can be used in engine calculations. They make it possible to regulate the piston stroke according to the combustion speed of the fuel.

Effect of the Composition of the Mixture

The mean velocity of flame propagation varies as the richness within the narrow limits of the richness used. The lag is great in lean mixtures. In rich mixture the lag is zero for benzol and of the order of one thousandth of a second for hexane. (See Table III, page 19.)

Effect of Compression Ratio

The effect of the compression ratio on the mean velocity of flame propagation was also investigated. The test results are given in Table IV, page 19.

The Shock and the Explosive Wave

The first apparatus gave us no information regarding the explosive wave, because we were never able to find it on the flame photographs. The second apparatus was constructed for the purpose of filling this gap. Despite the possibility of using the compression ratio of 7 and raising the temperature of the mixture to 115°C (239°F), the new apparatus very seldom gave us the black streak sought, corresponding to the formation of the explosive wave. Nevertheless, in an engine of the same piston displacement, knocking or detonation occurred as soon as the compression ratio exceeded 5, the cylinder being cooled by a stream of cold water. Under these conditions we were led to doubt that the knocking was produced by the explosive wave and we have been investigating as to whether some degree of discontinuity in the combustion of the fuels, easily producing the phenomenon of the shock, may have a systematic character.

We had noticed that the photographs given by the saturated hydrocarbons (hexane, heptane, gasoline) showed discontinuities not shown by the photographs obtained with the aromatic hydrocarbons. If these discontinuities had any relation to the shock, it should be possible to increase them and to make them more and more general in proportion as they are placed under conditions more favorable to the shock. For this purpose we conducted a large number of tests (about 400), while varying methodically the experimental conditions, namely, the time for the formation of the mixture, the ignition timing, the richness, the temperature, and the compression ratio. The following is a summary of our conclusions.

When, in general, the curve is continuous and the darkening which it outlines is progressive and continuous for benzol and its homologues, there are very frequently discontinuities of curve and of darkening for the saturated hydrocarbons which cause the shocks. The discontinuous records, however, do not seem to become more frequent in proportion as the conditions are more favorable for the production of the shock. The discontinuities noted are certainly indications of a less regular combustion and consequently of sudden variations in the engine power. Their frequency in a series of tests enables the classification of the fuels according to their fitness for this high compression ratio, but there is need of a more precise and constant index.

Elimination of Knock by Turbulence

Ricardo noted the effect of turbulence on the disappearance of knocking and, in order to increase the turbulence in engines, he invented a cylinder head for producing turbulence, as shown in Figure 10. Our test apparatus, in which the cylinder proper is separated from the explosion chamber by a pronounced constriction, likewise produced turbulence in the explosion chamber. We repeated the previous tests, after appreciably increasing the diameter of the constricted passage in the apparatus, so as to reduce the turbulence. We then obtained the explosive wave easily and regularly at the compression ratio of 7 and the initial temperature of 115°C (239°F).

Records Obtained with the Explosive Wave

The explosive wave is characterized by a black streak on the record, which is formed toward the end of the propagation of the flame, as shown in Figure 11 and photographs XXI to XXXVII. We refind here the aspect of the photographs obtained by Withrow. This aspect of the record is constant, and the photographs obtained with benzol never show this phenomenon. (Nos. I, II, III, for example.)

Effect of Temperature on the Records

The appearance of this black streak on the record if the test is made at a constant compression ratio and with gradually increasing temperature, indicates a temperature which is called the initial temperature of the explosive wave. If the temperature continues to be raised, it is found that the normal propagation no longer reaches the end of the combustion chamber, but is previously interrupted by the explosive wave. The black streak on the record, which represents it, becomes more and more pronounced as compared with the normal intensity. By increasing the heat, a temperature is reached, 150-160°C (302-320°F) for ordinary gasoline, at which the record no longer shows normal propagation, but only the spark and the explosive wave (photograph No. XXXVII).

In Figure 11 we have tried to represent the successive phases observed as the temperature is raised. These phases are also shown on the photographs. If increasing quantities of tetraethyl lead are added to a gasoline which yields, at 150°C (302°F), a record of the type F in Figure 11, one obtains successively all the records (E, D, C, B, A) in which the discontinuity of the detonation is decreasingly pronounced. To obtain this result, it is necessary to add only very small quantities of tetraethyl lead, of the order of 1/1000 of the volume of the gasoline. Every trace of an explosive wave can thus be eliminated. These additions do not seem to have any appreciable effect on the ignition temperature, which affords a new proof of the independence of these two phenomena and confirms the observations of Aubert, Pignot and Villey.

Classifying Fuels According to Their Resistance to Detonation

For a given initial temperature and compression ratio, the quantities of tetraethyl lead required to be added to a series of fuels to eliminate detonation may serve as a criterion of the tendency of these fuels to detonate. Unfortunately it is necessary to treat very small quantities with precision and handle a poisonous substance with pipettes, which is rather dangerous. Therefore this method of classifying fuels does not seem very practical.

We prefer the following method. A few preliminary tests determine the temperature at which one of the fuels, presumed to be of medium quality, yields a record showing the phase D or E in Figure 11. Then the whole series of fuels is tested without changing the compression ratio or temperature. The more normal the combustion, the less detonating the fuel will be considered. If one or two fuels of known detonating powers, evaluated by octane numbers, for example, are interpolated in the series, an octane number can be attributed, without great error, for each of the fuels tested.

The photographs show records corresponding to a series of fuels previously classified with the aid of a special engine. The differences shown are considerable for small differences in the octane number. Photographs XXXIII to XXXVII correspond respectively to the octane numbers 72, 66, 62, 57, and 50.

Identification of Fuels

Special engines give greater precision than the photographic method in determining the octane number. Such engines can give the octane number to within half a point, while the photographic method with our second apparatus can only give it to within about two points.

The photographic method, however, gives us a definite and incontestable record. A different photograph with the same apparatus indicates a different quality of fuel. The most important characteristics shown by the photographic records are the total time of propagation, the lag and the beginning of the detonation.

We would consider it of interest to add to the official description of a fuel showing the specific gravity, distillation curve, etc., explosion photographs, taken with a standard apparatus at certain predetermined temperatures, e.g., 125°, 135°, and 145° C (257°, 275°, and 293°F). We believe the photographic method could be advantageously employed in some such way.

Capital Importance of the Initial Temperature

The effect of the temperature on the appearance of the photograph, when the conditions of detonation are obtained, is considerable, as shown by photographs XXI to XXXII. These photographs were obtained with six different fuels, a test being made with each at 145°C (odd-numbered photograph) and at 136°C (the following even-numbered photograph). For example, photographs XXVII and XXVIII were obtained with the C.1.P. fuel at these two temperatures, the compression ratio being 7 and the richness 88 mm³/liter (1/11364) at the given temperature. It was found that the violence of the detonation was decidedly more pronounced in the test made at the higher temperature. This statement also holds true for the other five pairs of photographs. The phenomenon is perfectly systematic.

The influence of the initial temperature on the detonation records (but not on the other records) is such that it is necessary to be absolutely sure of its value in the explosion chamber before the test. Above all, it must be very uniform. Thus far we have used electric heating coils and, if the results are interesting, we think they will be still better and that a greater precision can be obtained in the identity of the records by improving the regularity and precision of the heating.

Tests Now Being Made

A third apparatus is now in use, in which the heating is effected by the circulation of hot oil around the cylinder and explosion chamber. The records obtained can, in fact, be classified with much greater precision. We have profited by this new apparatus to approach still more closely the conditions encountered in an engine. The combustion chamber is more compact, while retaining the necessary geometric shape, and the constriction is almost entirely eliminated. We think this apparatus might constitute a standard apparatus for the identifications of which we have spoken. The Service des Matières Premières de l'Aéronautique will henceforth employ this method for testing engine fuels.

SUMMARY

This report not only presents matters of practical importance in the classification of engine fuels, for which other means have proved inadequate, but also makes a few suggestions. It confirms the results of Withrow and Boyd which localize the explosive wave in the last portions of the mixture burned. This being the case, it may be assumed that the greater the normal combustion, the less the energy developed in the explosive form.

In order to combat the detonation, it is therefore necessary to try to render the normal combustion swift and complete, as produced in carbureted mixtures containing benzene (benzol), in which the flame propagation, beginning at the spark, yields a progressive and pronounced darkening on the photographic film.

We stated that the propagations of the gasoline and its constituents showed a considerable lag. The propagation which follows the lag is dim and incomplete, after which one often observes a suddenly increased darkening (photographs VI, VII, VIII, IX). The explosive wave, doubtless due to peroxides which had time to form during this delay to normal combustion, must originate as the rupture of an unstable state, analogous to the crystallization of a supersaturated liquid into which a crystal is dropped.

The antidetonants, of which tetraethyl lead is the most powerful, enable the attainment of better normal combustion, both in velocity (reduction of the lag) and in completeness. Hence the explosive wave cannot form (due to the absence or small quantity of peroxides) or, if it is formed, its power is diminished in proportion to the increase in the normal combustion.

In conclusion, we wish to express our gratitude to those who have aided us either materially or by their counsel.

Among the former we wish to acknowledge the generosity of Inspector General Seguin, Directeur du Service des Recherches de l'Aéronautique, as also of the management of the Société du Gaz de Paris, which is an important source of national fuels.

Among the latter, we wish to express our gratitude to Mr. Cotton, member of the Institute, and to Professor Mailhe and Villey of the Faculty of Sciences.

Lastly, we wish to express our very particular gratitude to Mr. Aubert, who has followed these tests since 1926 and who has often given us the moral support so much needed by investigators in the hours of disappointment.

Translation by Dwight M. Miner,
National Advisory Committee
for Aeronautics.

TABLE I

Gasoline	1	2	3
Compression ratio	7	7	7
Temperature in cylinder	56°	56°	61°
Atmospheric pressure	762 Hg	762	771
Fuel injected into cylinder per liter of cylinder volume, in mm^3	127 mm^3	127	127
Number of consecutive tests at one time	3	8	10
Delay between beginning of intake and compression (for homogeneity of mixture)	6 min.	6 min.	1 min. 30 sec.
Propagation time (in 1/1000 sec.) for distance of 10 cm (4 in.)	5.2, 5.3, 5.8, mean 5.6	5.2, 4.8, 6.2, 7.2, 5.6, 6.3, 6.7, 7.2 mean 6.0	7.5, 6, 5.8, 7.2, 6.8, 7.4, 6.6, 5.7, 5.8, 9 - mean 6.8
Mean velocity per second deduced from above figures	18 m	17 m	15 m
Lag (time between spark and beginning of propagation)	1, 1.7, 2.6, mean 1.7	1.2, 1, 3.1, 3.5, 2.1, 1.9, 2.6, 2.6. mean 2.1	3.1, 1, 3, 2, 2.5, 3, 2.3, 1, 1.3, 4 mean 2.3
R e m a r k s	All the photos show discontinuities of darkening	Half the photos show discontinuities	Four photos in ten show discontinuities

(mm x .03937 = in.) (mm^3 x .000061 = cu.in.) (cm x .3937 = in.)

(m x 39.37 = in.) (°C x 1.8) + 32 = °F

TABLE I (Cont'd)

Gasoline	4	5	6
Compression ratio	7	6.4	6.4
Temperature in cylinder	63°	63°	66°
Atmospheric pressure	759 Hg	770	764
Fuel injected into cylinder per liter of cylinder volume in mm^3	127 mm^3	107	107
Number of consecutive tests at one time	5	3	8
Delay between beginning of intake and compression (for homogeneity of mixture)	1 min. 30 sec.	1 min. 30 sec.	1 min. 30 sec.
Propagation time (in 1/1000 sec.) for distance of 10 cm (4 in.)	4.7, 5, 6, 5.2, 5.3 mean 5.2	8.7, 5.8, 9.2 mean 7.9	5.6, 5, 4.1, 7.8, 4.9, 5.7, 13.2, 5.1 mean 6.4
Mean velocity per second deduced from above figures	19 m	13 m	16 m
Lag (time between spark and beginning of propagation)	1.2, 1, 2, 1.1, 1.2 mean 1.3	4.2, 1.9, 5 mean 3.9	1, 1, 0.4, 3, 1.3, 1.5, 5.7, 2.1 - mean 2
Remarks	Two photos show discontinuities	Two photos show discontinuities	Half the photos show discontinuities

TABLE I (Cont'd)

Gasoline	7	8	9
Compression ratio	5.9	5.9	7
Temperature in cylinder	66°	64°	102°
Atmospheric pressure	762 Hg	760	762
Fuel injected into cylinder per liter of cylinder volume in mm^3	127 mm^3	116	
Number of consecutive tests at one time	5	6	
Delay between beginning of intake and compression (for homogeneity of mixture)	1 min. 50 sec.	1 min. 30 sec.	6 sec.
Propagation time (in 1/1000 sec.) for distance of 10 cm (4 in.)	4.9, 5, 4.9, 8.8, 6.8 mean 6.2	5.2, 6, 4.4, 6.5, 6.8, 6.7 mean 5.9	2.4, 6.5, 11, 7.3, 7, 5.8 mean 8.6
Mean velocity per second deduced from above figures	16 m	17 m	11.5 m
Lag (time between spark and beginning of propagation)	1.6, 1.7, 1.7, 3.4, 1 mean 1.4	2.3, 2.2, 2.0, 2.5, 2.7, 1.9 mean 2.3	6.5, 1.7, 5.4, 4.7, 3.7, 2.2, 3.7
Remarks	One photo discontinues	Two photos discontinue	All the photos show a sudden darkening after a very faint beginning

TABLE I (Cont'd)

Benzol 90	2	3	4
Compression ratio	7	7	7
Temperature of cylinder	62°	63°	63°
Atmospheric pressure	762 Hg	759	759
Fuel injected per liter of cylinder volume in mm³	105 mm³	127	105
Number of tests made	10	5	3
Delay (for homogeneity before compression)	6 min.	1 min.30 sec.	1 min. 30 sec.
Propagation time (in 1/1000 second)	5.3, 5, 4.2, 4.5, 4.2, 4.9, 4.6, 6.6, 6, 6 mean 5.1	3.9, 4.6, 5, 4.2, 4.6 mean 4.4	5.4, 8.5, 5.1 mean 6.1
Mean velocity per second	20 m	23 m	16.5 m
Lag (between spark and beginning of propagation)	0.7, 1.3, 0.2, 0.6, 0.7, 1, 0.9, 0.5, 1, 1 mean 0.8	0.4, 0.6, 0.5, 0.7, 0.6 mean 0.6	1.5, 3,7, 1 mean 0.2
Remarks	All photos show continuous and progressive darkening	Continuous and progressive darkening	Only one discontinuity

TABLE I (Cont'd)

Benzol 90	7	8	9
Compression ratio	5.9	5.9	7
Temperature of cylinder	63°	64°	105°
Atmospheric pressure	746 Hg	-	-
Fuel injected per liter of cylinder volume	127 mm³	96	127
Number of tests made	5	3	3
Delay (for homogeneity before compression)	1 min. 30 sec.	1 min. 30 sec.	6 sec.
Propagation time (in 1/1000 sec.)	3.1, 3.7, 2.8, 3.5, 3.8 mean 3.4	5.1, 4.3, 4.9 mean 4.7	7.3, 8, 8 mean 7.8
Mean velocity (per second)	30 m	21.5 m	13 m
Lag (between spark and beginning of propagation)	0.6, 1, 0, 0.6, 0.4 mean 0.5	1.7, 1, 1.6 mean 1.4	3.5, 2.2, 2.9 mean 2.9
Remarks	Continuous and progressive darkening	Continuous and progressive darkening	Two photos show discontinuities

TABLE II

Propagation Time of Flame in Thousandths of a Second

Fuel		Compression ratio	Temperature of cylinder 15°	50°	60°	100°
C_6H_6		5.9, 7	8	3.3, 3.5		
Benzol 90		5.9, 7	8		5, 4.2	
Benzol (auto)		5.9, 7		5.5, 4.5		
Hexane		5.9, 7	8 - 8	4.2, 4		4.6
Heptane		5.9, 7		5 - 5		5
Light gasolines	A	5.9, 7	(a)	5.6, 7		
	B	7	(a)	5		5.1
	C	7	(a)	5.5		4.9
	D	7	9	7		4.1
	E	7	9	6		4.4
	F	5.9, 7	6.7, 5.6			
Heavy gasolines	B'	7	(a)	15		
	C'	7		6.5		
	D'	7		16		
B' + 30% benzol		7		6		
D' + 30% benzol		7		6.4		

(a) Ignition impossible.

TABLE III

Temperature of cylinder, 95°C (203°F). Compression ratio, 7		
Richness of mixture (mm^3/liter)	Time of propagation through 10 cm (about 4 in.) of pure gases, in thousandths of a second	
	Benzene (C_6H_6)	Hexane (C_6H_{14})
116	4.4	4.6
103	3.4	4.2
88	4.2	9.1
75	5.9	8.6
60	6.6	10.1

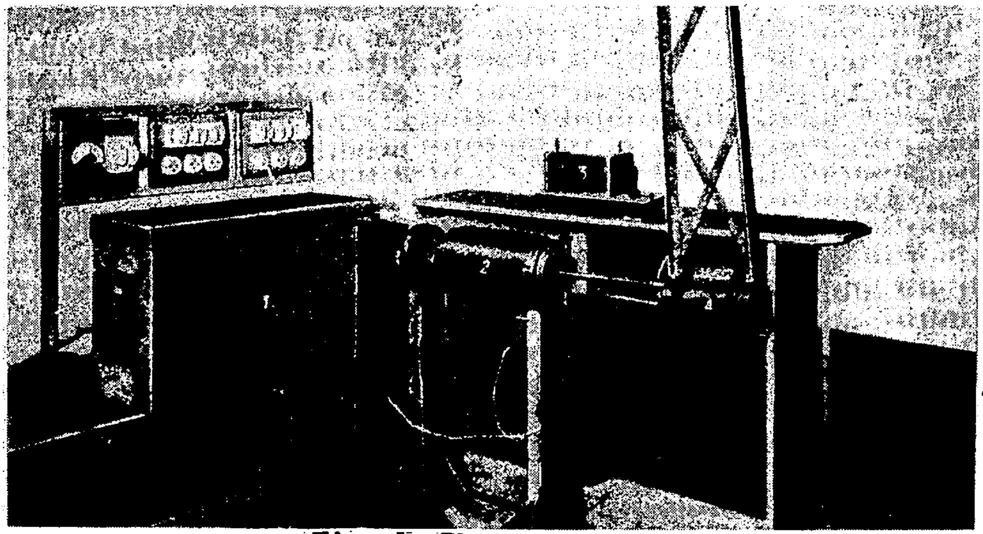
TABLE IV

Temperature, 61°C (141.8°F). Richness of mixture, 127 mm^3/liter				
	Time required for flame to traverse explosion chamber, in thousandths of a second		Lag between spark and beginning of propagation, in thousandths of a second	
	Compression Ratio			
	5.9	7	5.9	7
Gasoline	5.1	6.9	2	2
Benzol 90	3.5	4.7	0.5	0.6

TABLE V

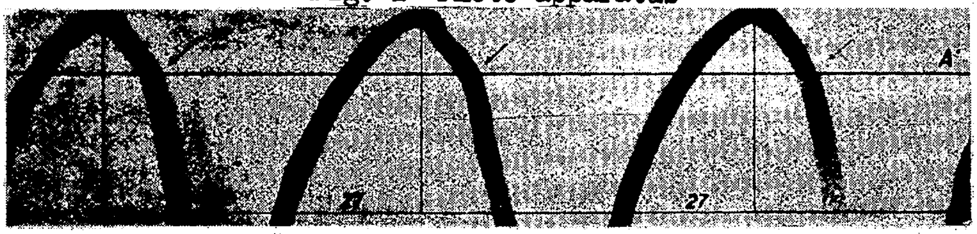
Conditions under Which the Photographs Were Obtained

Photograph	Fuel	Temper- of mixture degrees	Compression ratio	Richness in mm^3 per liter of mixture
I	Benzol	62	7	107
II	-	-	-	-
III	-	-	-	-
IV	Gasoline S 2	56	7	127
V	-	56	7	127
VI	-	100	7	127
VII	-	63	6.4	107
VIII	-	100	4.5	127
IX	Gasoline S	50	5.9	140
X	Gasoline S-Benzol (mixture 70-30)	50	5.9	116
XI	Gasoline	50	5.9	116
XII	Hexane + 4% Amylene	50	5.9	116
XIII	Heptane	54	5.9	88
XIV	Gasoline S 1	53	5.9	155
XV	Gasoline S 3	54	7	116
XVI	Benzol (auto)	15	5.9	191
XVII	Hexane	50	5.9	103
XVIII	-	-	-	-
XIX	-	15	-	191
XX	Hexane + 1% Amylene	50	5.9	103

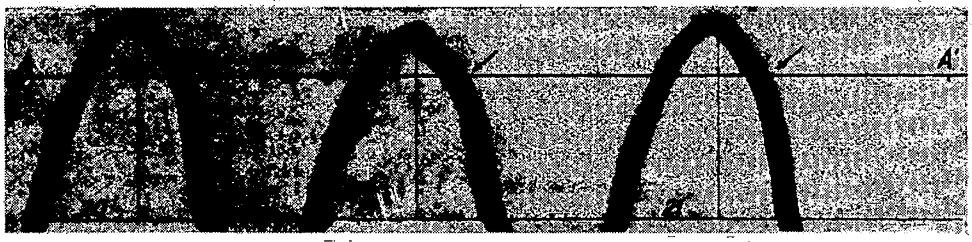


1. Camera with drum inside
2. Cylinder surrounded by electric heaters
3. Induction coil
4. Ram

Fig. 1 Photo apparatus



Esso gasoline (103 mm^3/ liter), t = 148°C v = 2.86 m/sec



Ordinary gasoline (103 mm^3/ liter), t = 148°C v = 2.88m/sec.

Fig. 8 Esso and ordinary gasoline.

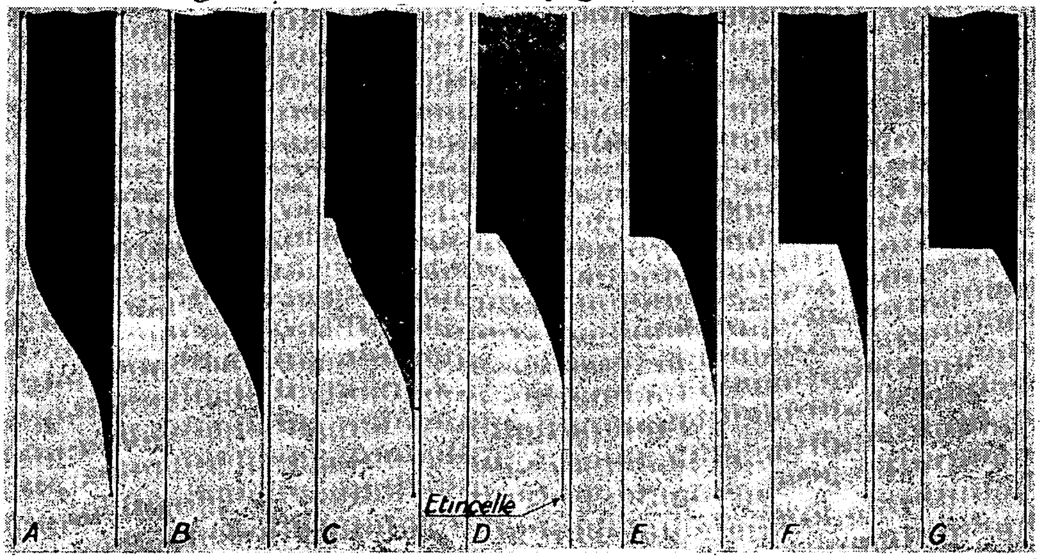


Fig. 11 Variations in the record due to raising the initial temperature.

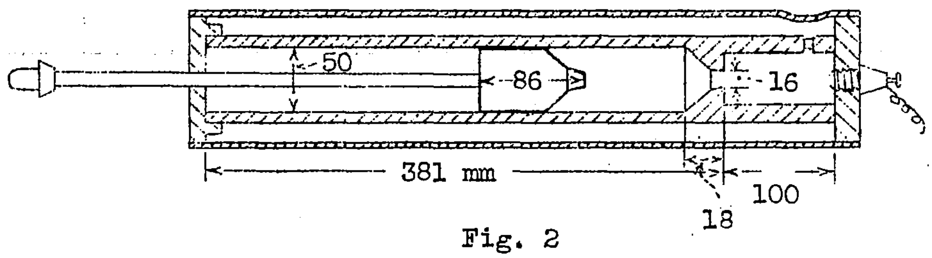


Fig. 2

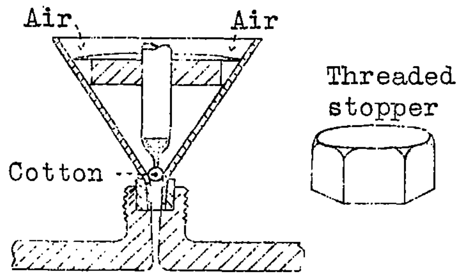


Fig. 3 Device for obtaining mixture

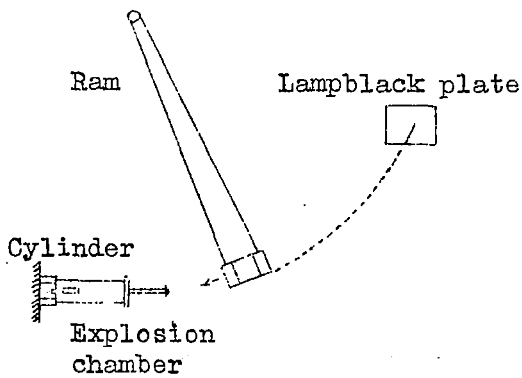


Fig. 4

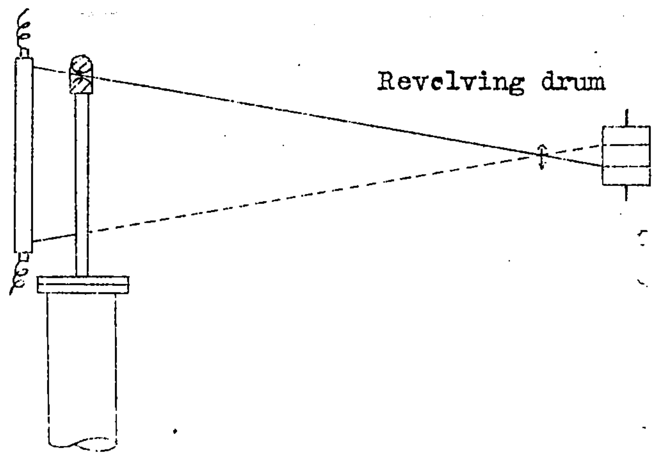


Fig. 5 Device to record motion of piston.

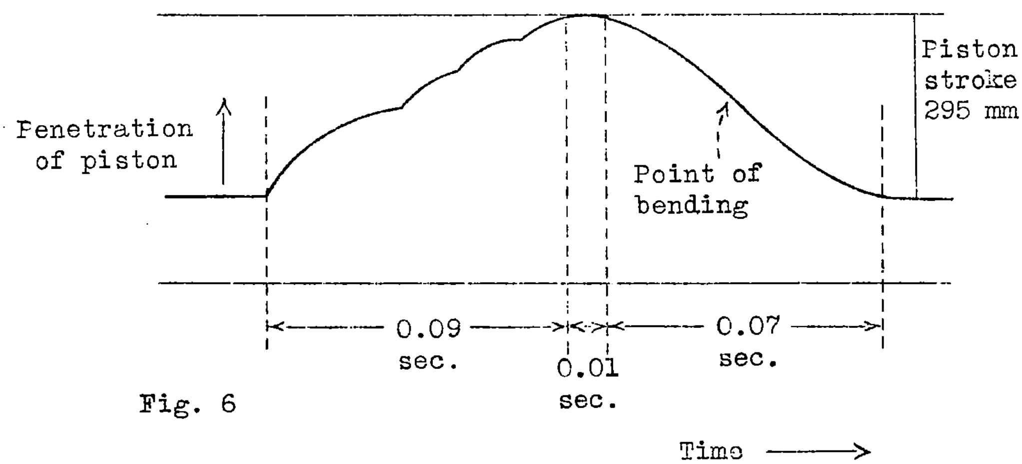


Fig. 6

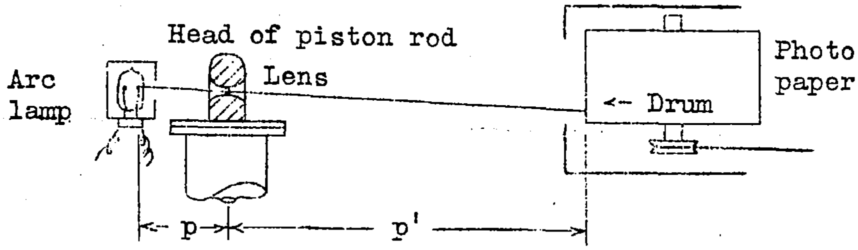


Fig. 7 Magnifying device. The magnification is given by the ratio $\frac{p'}{p}$

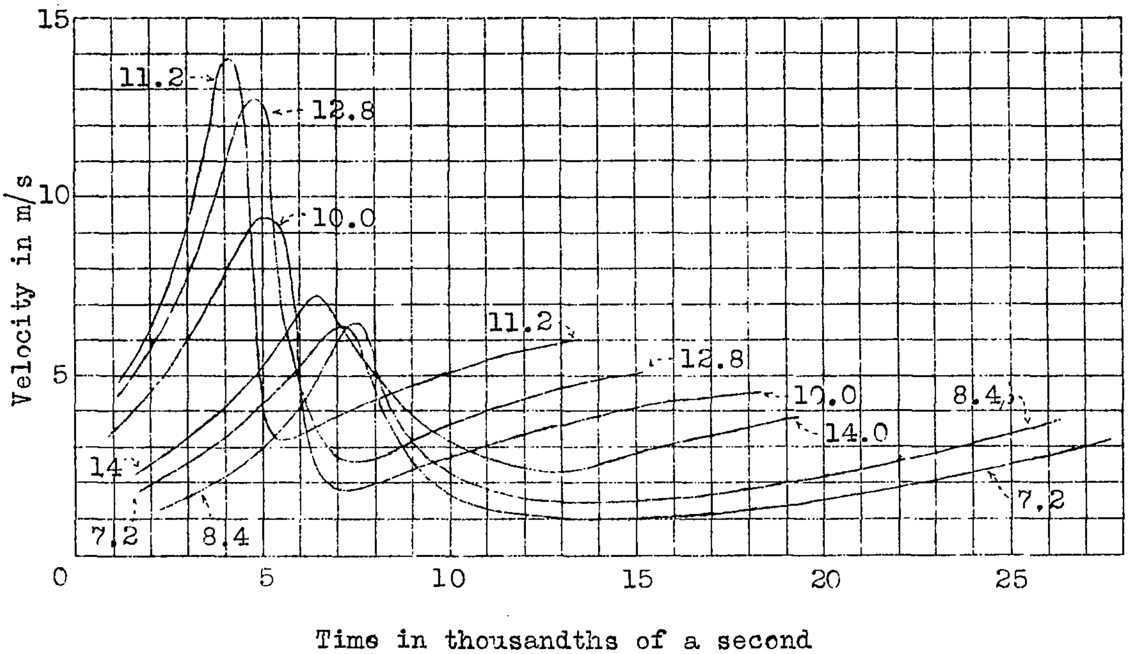


Fig. 9 Cyclohexane. Velocity of flame front plotted against time in thousandths of a second.

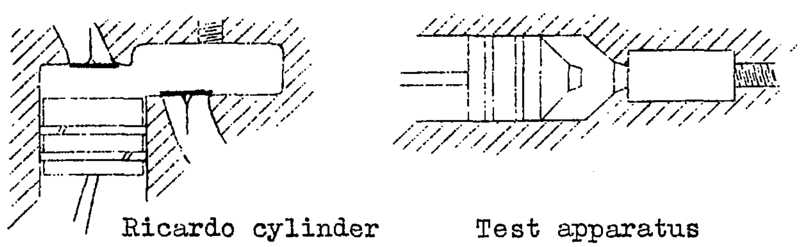
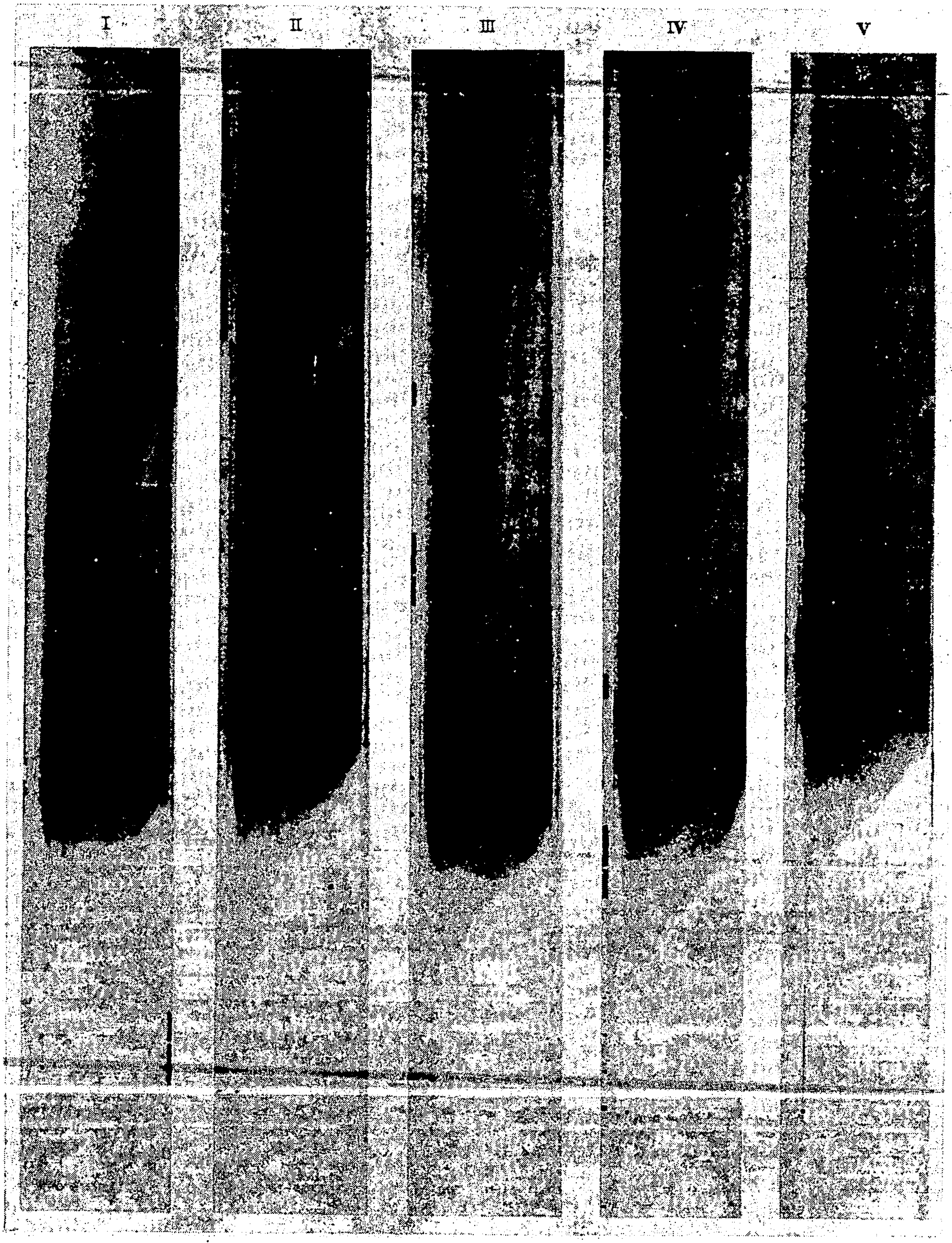


Fig. 10 Comparison of Ricardo turbulence cylinder head and the test apparatus.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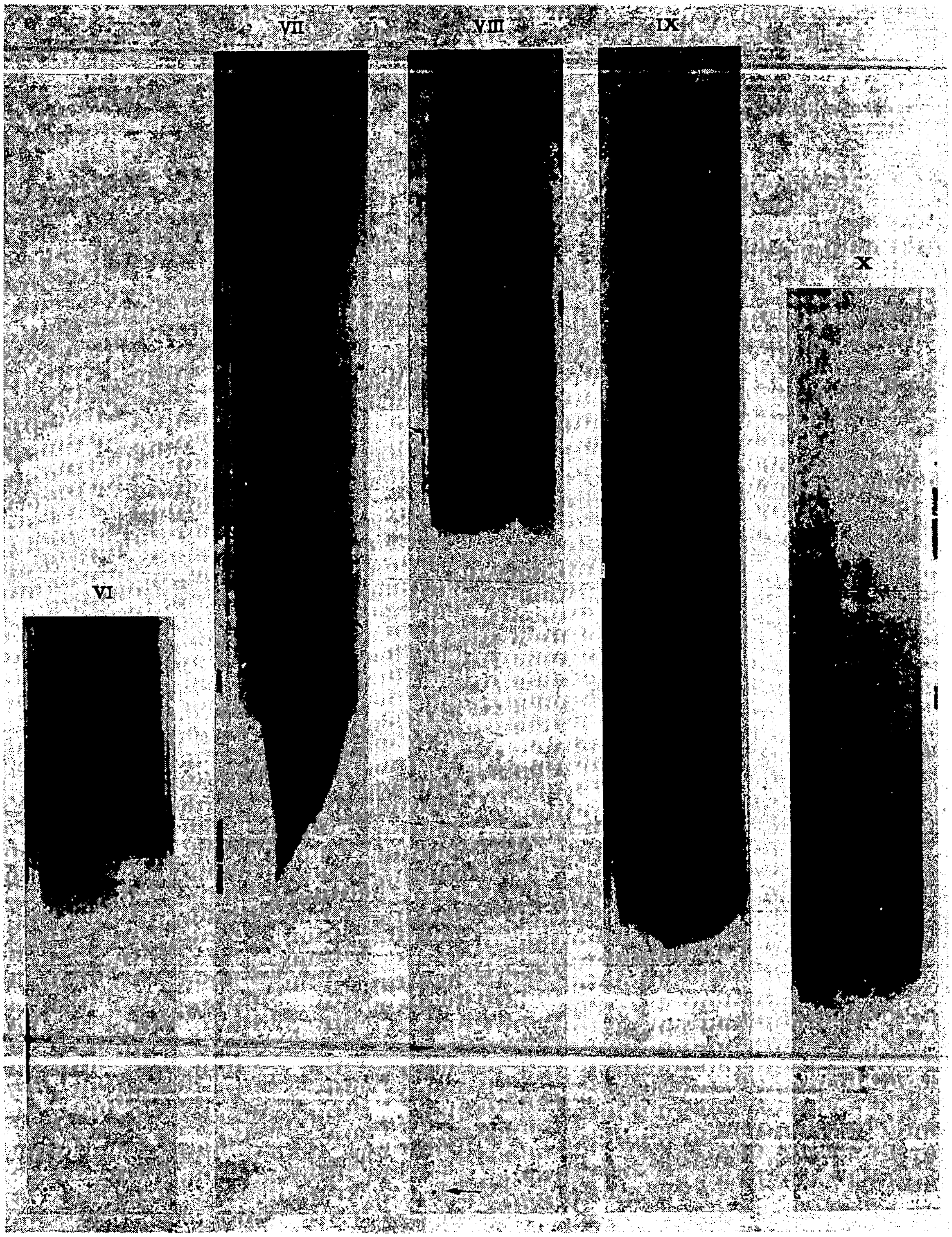
II
III
IV
V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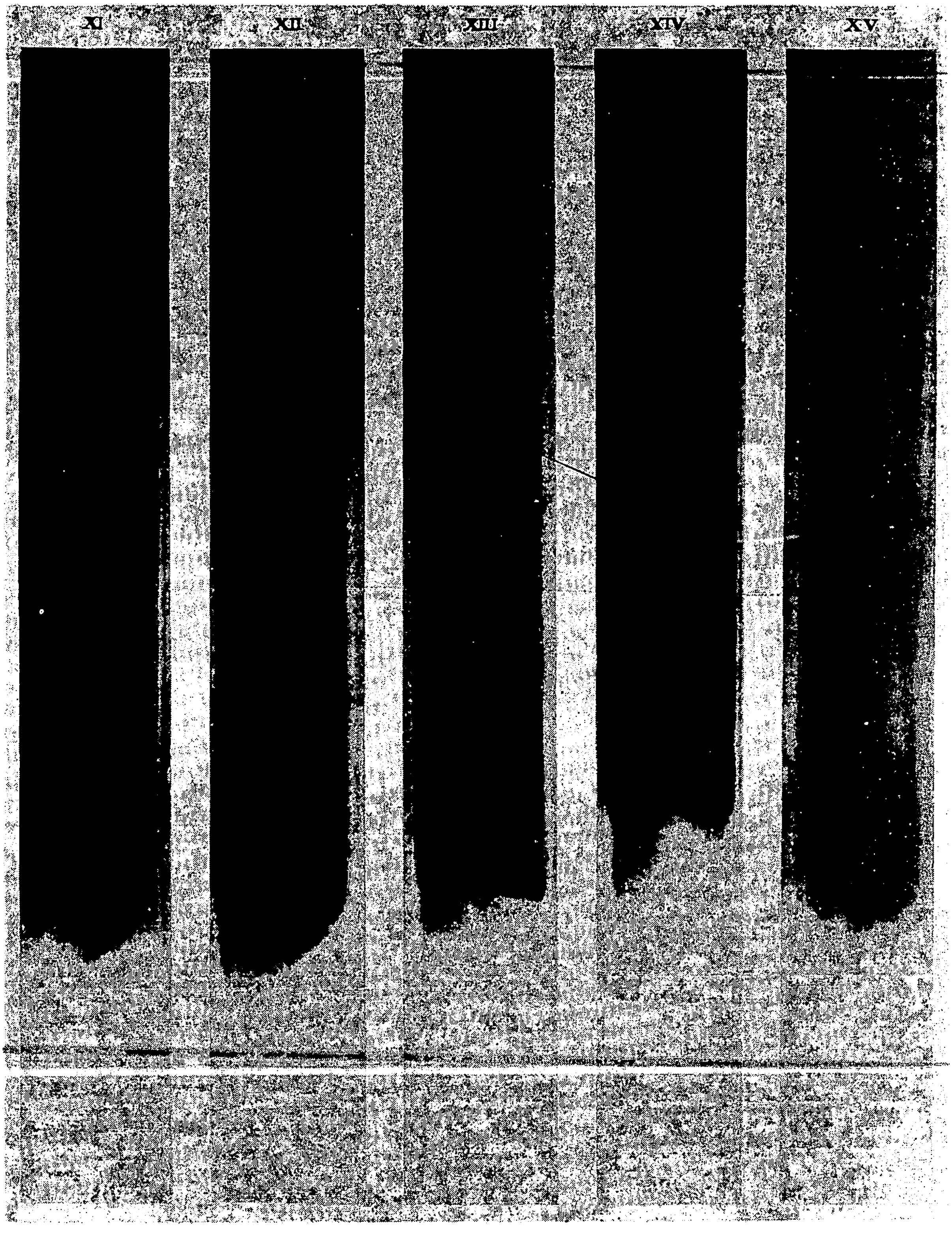
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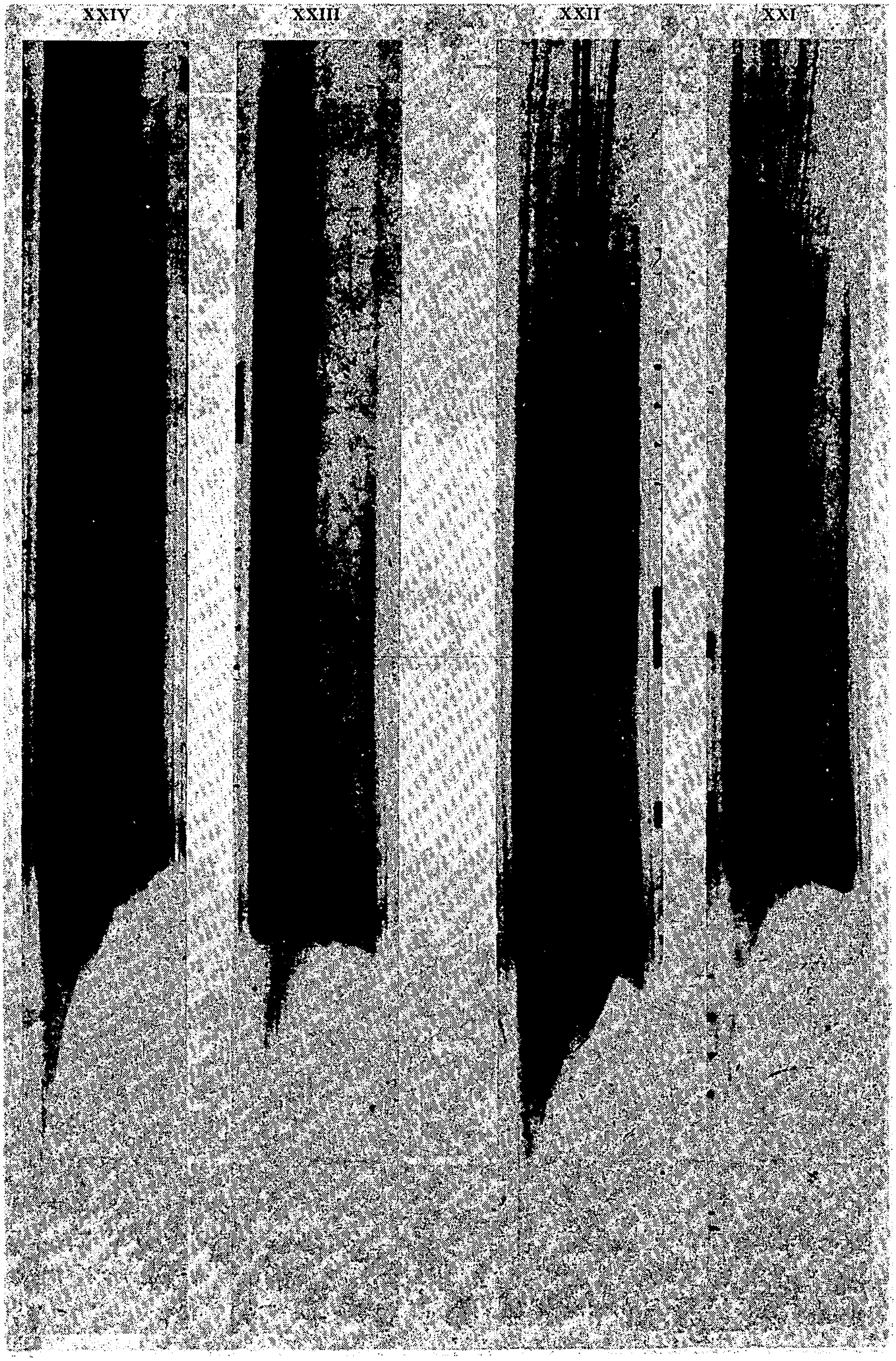
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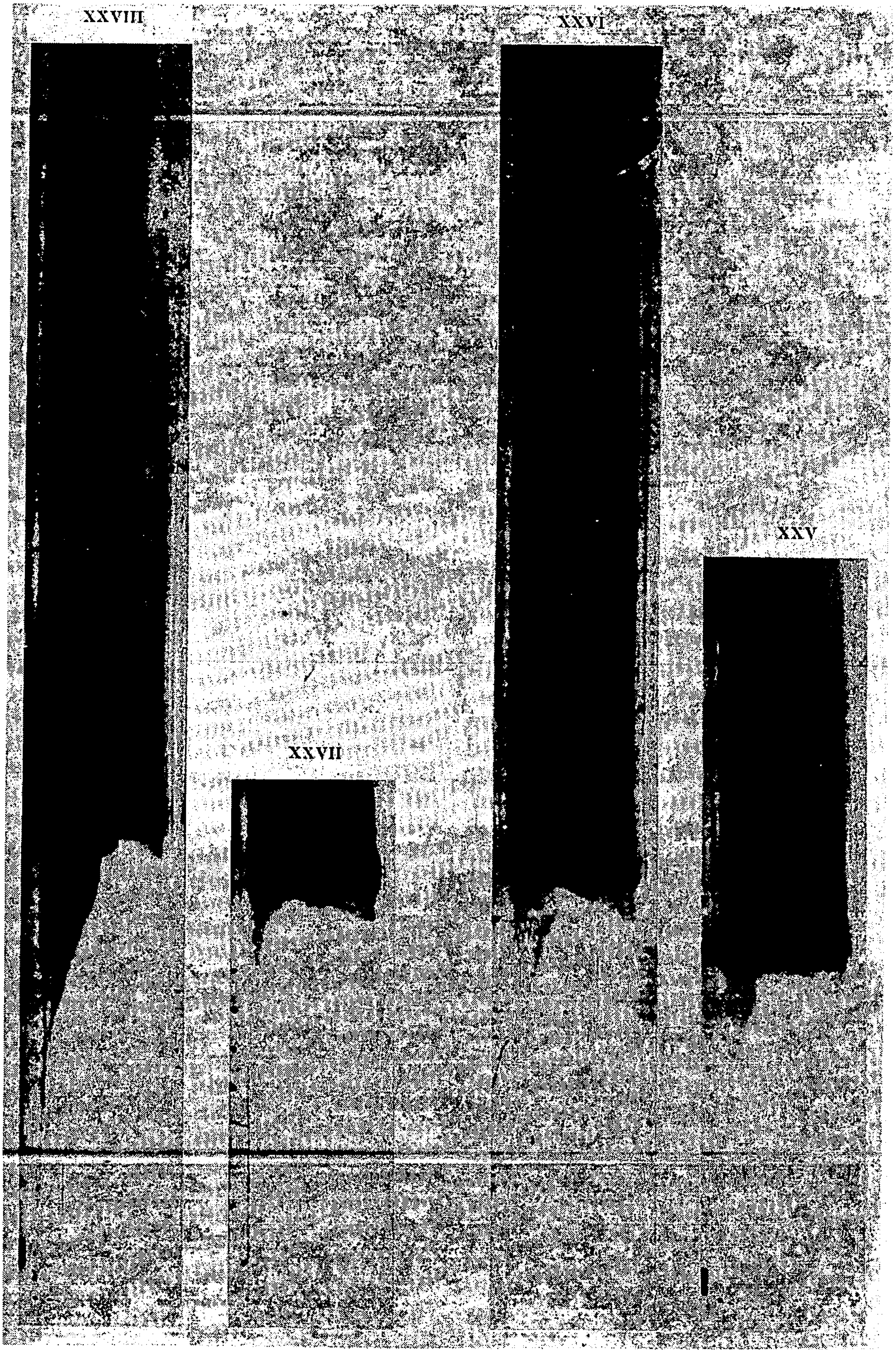
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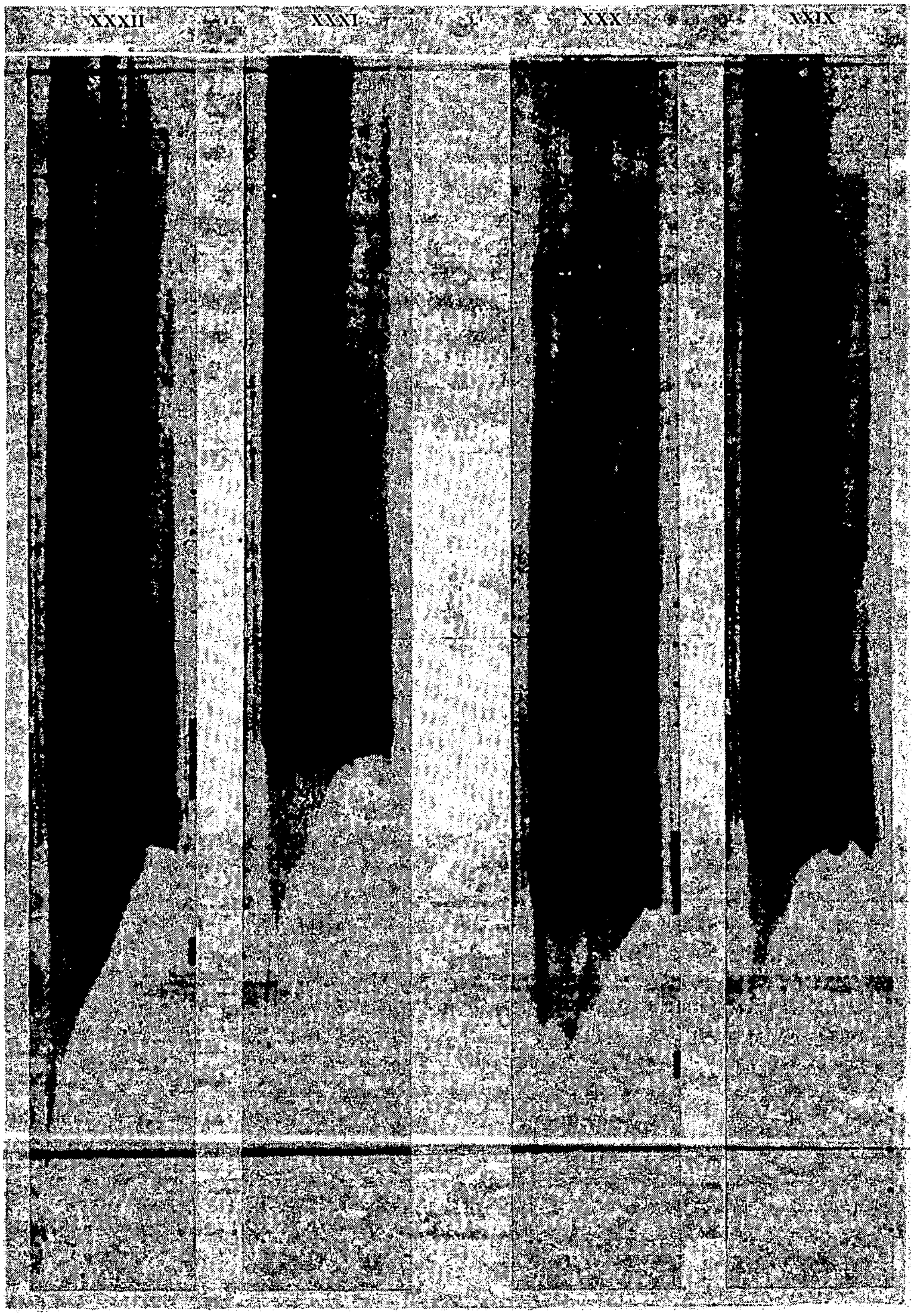
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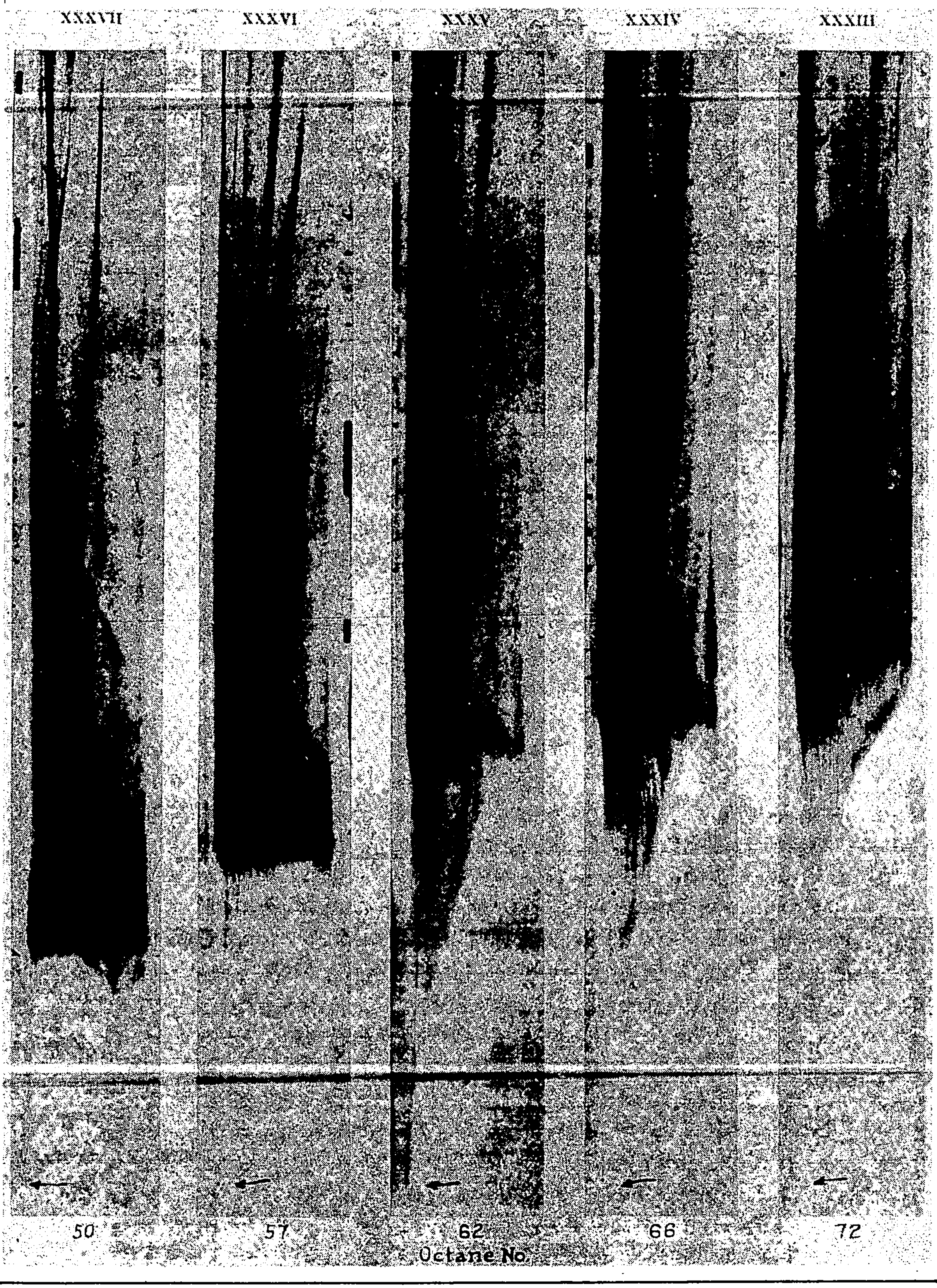
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Octane No.